JFSP Smoke Science Plan Final Report Executive Summary

Background: The Smoke Science Plan (SSP) was the guidance and organizational tool of the Joint Fire Science Program for smoke research from 2011 until 2016. It helped to guide the funding and management of 41 research and development projects under four thematic areas. Since its inception in 2011, 29 smoke science projects have been funded. An additional 12 legacy projects, addressing research needs identified in the SSP, were added to the portfolio for a total of 41 projects considered as part of the SSP.

Theme I Smoke Emissions Inventory: Research under this theme was purposed to address the science needed to support an accurate national wildland fire emissions inventory system, improve emission factors, and apply improved emissions inventory tools to evaluate fire's contributions to regional ozone and particulate matter (PM) loadings.

Research compared the effectiveness of top down (e.g., satellite remote sensing) and bottom up (e.g., accounting practices) tools for constructing inventories. Results suggested that fuel loading and fuel consumption were large sources of uncertainty in any large-scale inventory (project 12-1-7-01) confirming earlier modeling comparisons in Theme II (project 08-1-6-10). Methods to improve fuel loading estimates have been identified and an ongoing research project is addressing improving fuel mapping and evaluating its spatial representativeness (project 15-1-01-1). Consumption, another component of emission inventories, was addressed in a Theme II project (08-1-6-10). Model results compared well with field measurements; however, separating flaming from smoldering and treating different fuel strata remain as issues that contribute to uncertainty.

Both laboratory and field studies measured emission factors for prescribed fire and peat fuels (projects 09-1- 3-01, 11-1-5-12 and 11-1-5-16). The complex nature of carbon emissions, especially their volatility and role in generating secondary organic aerosols were studied in depth (projects 09-1-3-01, 14-1-03-26, 14-1-03-44). New understandings have led to new chemical mechanisms for modeling smoke impacts on ambient air quality. These are being used to improve air quality models in a few ongoing research projects (12-1-8-31 and 14-1-03-44

Projects evaluated the relative contributions of fire smoke to both ozone and $PM_{2.5}$ in the US producing a relative ranking of counties where fire is most likely to contribute to national ambient air quality standard exceedances (projects 11-1-6-06 and 12-1-8-31). Tools developed in this research are currently being used at state and local levels to help in the air quality planning process and in retrospective analysis of Exceptional Events.

***Theme II Fire and Smoke Model Validation*:** Research under this theme identified the scientific scope, techniques, and partnerships needed to objectively validate smoke and fire models using field data.

Smoke models generally are hindered by the lack of accurate fuel loading data, especially data that represents the three-dimensional distribution of fuel loading across the fire area (projects 08-1-6-01, 09-1-4-01). Additionally, plume rise is often over-predicted by commonly used simple techniques, which miss the influence of multiple plume cores, and result in significant errors in predicting smoke transport (projects 08-1-6-04, 09-1-4-01). JFSP-sponsored research has verified that the more models are tested in the field or are run through post-fire scenarios, the clearer it becomes that a key need is more and better data sets to evaluate them (project 08-1-6-10, Smoke and Emissions Model Intercomparison Project - SEMIP). Fire and smoke model evaluation and validation require multiple scientific disciplines and data sets that cross those disciplines. It has become clear that to improve fire behavior models, which are an essential component of smoke modeling, work must move to experimental fires of larger size, higher fuel loadings, and elevated burn intensities from previous efforts (project 11-2-1-11, Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment - RxCADRE). It is also clear that for smoke modeling itself such field work must also move into complex fuels with greater fuel loading (than the grasslands previously studied) and higher intensity fires (project 13-S-01-01). An interagency study plan is nearing completion that will identify approaches to gather data needed to validate smoke models (project 15-S-01-01, Fire and Smoke Model Evaluation Experiment - FASMEE).

Superfog, a condition where smoke and fog mix to reduces visibility enough to cause safety hazards, was researched and advances made at understanding the atmospheric conditions necessary for such events to occur (project 09-1-4-05). This work was complemented by work on low intensity and sub-canopy smoke transport (projects 09-1-4-01 and 09-1-4-02). In these studies, and others (notably project 12-3-1-06), the need for gridded weather data at high terrain resolutions was necessary to properly simulate combustion, emissions, atmosphere/smoke interactions, and smoke dispersion.

Theme III Smoke and Populations*:* Research under this theme was purposed to quantify the impact of wildland fire smoke on population centers and on fire workers, as well as to elucidate the mechanisms of public smoke acceptance in light of the needed balance between human smoke exposure risk and ecosystem health risk. Ultimately, this research was envisioned to help in the development of a national smoke hazard warning system/methodology based on best science.

In recent years it has become clear that smoke from fires, especially from “megafires,” can impact not only the wildland urban interface but also large urban areas some distance removed from the fire itself (projects 11-1-7-02 and 11-1-7-04). With more people exposed to wildland fire smoke comes the need to better understand how smoke affects human health, the levels of smoke that create different public health concerns, and how to best warn the public when smoke events are imminent. Also, as fires become more frequent and larger, and the demands on firefighting resources increase, the need arises to understand the effects of extended exposure on firefighter health.

The first major objective of the theme was to address the health impacts of wildland fire smoke on fire workers and the public. Four projects were funded and all are ongoing, but two projects have significant preliminary findings. Project 14-1-04-16 is investigating the toxicity of smoke emissions, marking the first time that the cardiopulmonary toxicity and mutagenicity of emissions from wildland fuels have been studied. Fuel types and combustion phases were found to dramatically alter the emission characteristics, mutagenicity, and lung toxicity of wildland fire smoke. The findings have prompted the Environmental Protection Agency (EPA) to undertake further research into the effects of fire emissions on pulmonary function and toxicity, neurobehavioral changes, and cardiovascular function and toxicity from acute and sub-chronic inhalation exposure of smoke. The EPA also is interested in investigating the effects of aged wildland smoke mixed with urban air pollution. Project 14-1-04-9 is characterizing the health and economic burden of wildland fire smoke, representing the first attempt to quantify this across the continental US over multiple years. Work is showing that although effects differ from year to year, wildland fires pose a significant burden to public health on an annual basis. Populations in California, Idaho, Oregon, Louisiana, and Georgia are most affected. Project 14-1-04-5 is working to develop models to identify vulnerable populations that can assist public health agencies in targeting messages and interventions during wildland fire events. Project 13-1-02-14 is developing a set of risk-based exposure criteria for wildland fire fighters, which could be included in future drafts of NWCG's *Wildland Fire Personnel Smoke Exposure Guidebook.*

The second objective focused on the public's perception and tolerance for smoke. The three projects funded by JFSP represent the only existing social science research on wildland fire smoke for the US. Findings confirmed that effectiveness of public smoke messaging is increased when the background of the audience, including the types of vegetation types they are familiar with and past experience with fire, is aligned with communication goals (project 10-1-3-02). The two strongest predictors of public tolerance for smoke from wildland fires are being aware of prescribed fire's benefits and trust in public fire managers (projects 10-1-3-07, 12-3-01-21). These findings will help frame wildland fire smoke messages to the public.

The third objective of this theme was to determine how to use information on health effects and public perceptions of risk to develop public health smoke messages during large fire events. To determine the best means of communicating smoke hazards to the public, JFSP funded three projects that are actively working together to develop an operational smoke hazard warning system (projects 13-C-01-01, 14-1-04-5, 15-1-02-4). In addition to advances in aggregating and distilling many complex datasets related to fire, smoke, and air quality into a central repository necessary for predicting smoke events and developing a smartphone application that include a visual range assessment tool, these projects have created a broad collaboration with the National Weather Service, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, EPA, Center for Disease Control and Prevention, and others to guide messaging and products and to create a collective vision for moving forward. The initial operational outlet of the Smoke Hazard Warning System is EPA's existing website, *AirNow*.

Theme IV Climate Change and Smoke: Research under this theme was purposed to better understand implications of climate change on wildland fire smoke and of wildland fire smoke on climate change using United Nations Intergovernmental Panel on Climate Change (IPCC) 2013 emissions scenarios for guidance. Research under this theme addressed black carbon generated from fire smoke, potential impacts from megafires on large urban areas, and simulation of future smoke impacts in under future potential climates.

Research was funded to quantify potential contributions of fire smoke to ambient black carbon concentration and deposition in the Artic and other regions (projects 10-S-2-01 and 11-1-5-13). Results have quantified: 1) fire emission's contributions to the black and brown carbon components of PM and 2) source regions and meteorological situations leading to black carbon deposition. One these modeling studies simulated potential black carbon deposition patterns in the northwestern United States (project 11-1-5-13), while the other developed an on-line tool for assessing potential for wildland fire black carbon artic transport.

Future megafires and their potential impacts, especially on urban areas, were estimated in two projects (projects 11-1-7-02 and 11-1-7-04). A special study paper addressed the state of science in coupled climate change, ecosystem, fire and smoke simulation modeling and suggested preferred approaches to working with the complex chain of interacting models. A second special study paper summarized the contemporary understanding of future fire and smoke on the climate system. Finally, two continuing studies are considering the impact of IPCC emissions-dependent climate projections on smoke and air quality in the U.S. and specifically in the southeastern U.S. through the mid-21st century (projects 13-1-01-4 and 13-1-01-16).

Remaining Challenges as Seen by the JFSP Smoke Science Advisors After Consideration of the Research Accomplished Under the SSP

A key smoke chemistry question remains about just how much understanding of this complexity is necessary for smoke management purposes. The absence of a nationally implemented fire inventory methodology, applied across all ownerships and fire types (wildfire, prescribed fire, agricultural burning), means smoke emission inventories are likely to continue to be inconsistent, uncertain, and potentially biased. Most projections for the western U.S., regardless of the specific emission scenario chosen, suggest a warmer drier climate with more extreme weather events so that fuel loadings and future fire occurrence become harder to estimate. Projections for other regions of the US are less clear. Because both fire and the smoke it generates occur, by and large, at local scales, whereas climate change analysis tools are most valid at global scales, differences in spatial scale and the associated controlling processes must be bridged for before these studies can be considered to be particularly useful for future planning.

As climate and demographics shift in the USA, health impacts from smoke will become of greater concern, especially understanding effects of mixes of smoke and urban pollution. As megafires increase, smoke transport into large urban centers will increase, changing needs for public warnings and education. And the long-term impacts on fire workers need to be studied, if not by JFSP, then by programs dedicated to this task. Increased use of models for developing information for health and safety alerts will necessitate improving models; such improvements must come from field data and theoretical work (see FASMEE). Smoke plume rise, secondary organic aerosols, how differing vegetation complexes and even phenologic stages of plant growth affect emissions, atmospheric chemistry changes during long-range transport—all of these issues will need further consideration and research.

Prescribed fire will come under more scrutiny and perhaps even subject to air quality restrictions in areas of the country designated as “non-attainment” for ambient standards for ozone and particulate. Such restrictions, however, may be a lesser worry if wildfire smoke emissions become “politicized” due to health impacts to urban populations. Both fire behavior and smoke models suffer from 1) a lack of computing power to run models with physics that are close to simulating reality and 2) a fundamental need for better understanding of the processes involved and the scientific talent needed to resolve these processes into mathematical formulae. Although a need exists to validate and test smoke mitigation practices in the field, such work may be overwhelmed by the rapid change in fire ecology resulting from a warming climate and catastrophic weather events.

Finally, it must be recognized that climate-driven processes are stochastic and non-stationary meaning they will always remain, to a certain degree, unpredictable. The past is not a good predictor of future events, especially regarding extreme weather behavior. Thus smoke impacts from future fires in a changing climate will remain highly uncertain. JFSP supported research has served to illustrate the breadth of potential for future smoke impacts. Continued research by the climate change and fire science communities will lead toward more useful, emissions-based regional climate and associated ecosystem projections. As these improvements develop JFSP may wish to consider further investment in the fire and smoke consequences of climate change.